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DRAWINGS ATTACHED

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(54) HIGH SPEED SURFACE FINISHING METHOD

(71) We, KABUSHIKI KAISHA SHIKISHIMA TIPTON, of No. 1, Toyoshiro-cho, Minami-ku, City of Nagoya, Aichi Prefecture, Japan, a Body Corporate organized and existing under the law of Japan, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to a method of surface finishing workpieces within a barrel of an equilateral polygonal cross-section gyrating at a high speed.

In the past, there have been proposed various forms of the surface finishing method referred to. For example, British Patent Specification No. 1,047,703 to H. Kobayashi discloses a surface finishing method comprising loading a mixture of workpieces and granular abrasives into at least one barrel having an internal cross-section in the shape of an equilateral polygon having from five to eight sides in such a manner that the mixture fills about one half of the barrel, and causing the barrel to gyrate about a fixed axis parallel to the axis of the barrel but not passing through the interior of the barrel while maintaining the barrel in a fixed orientation, at such a speed that the centrifugal force on the mixture in the barrel is greater than the force of gravity thereon so that relative movement occurs between the mixture and the abrasives in the free surface layer only of the mixture in the barrel and successive portions of the mixture are brought into and removed from the surface layer by the gyration of the barrel.

According to the surface finishing method just outlined the barrel may revolve about the said fixed axis in one direction while at the same time it rotates about its own axis in the opposite direction so as to maintain the barrel in the fixed orientation. Thus it will be appreciated that the barrel gyrates with the ratio of the number n of rotations to the number N of revolutions in unit time remaining unchanged or equal to minus one. The term "minus" means that the rotation is effected in the direction opposite to the direction of revolution. While this ratio of minus one generally gives satisfactory results it has been found that, if the ratio is greater or less than minus one, the operation may become very dangerous unless the ratio of the radius R of revolution (i.e. distance between the said fixed axis and the axis of the barrel) to the radius r of the circumcircle of the polygonal cross-section of the barrel is properly selected.

Also U.S. Patent No. 2,937,814 to A. Joisel discloses a ball crusher comprising a plurality of circularly cylindrical tubs gyrating at a high speed and teaches the preferred relationship between the distance from the axis of the crusher tub to the axis of the associated rotating frame and the inside radius of the tub and between the speed of revolution of the tub in relation to the frame and the speed of rotation of the frame. The latter patent is based on the phenomena that a mass comprising a mixture of workpieces to be crushed and crushing balls falls downwardly along the internal wall of the tub while it maintains a segmentally cylindrical shape substantially similar to the shape in which the mass was initially loaded in the tub or while the mass in the segmentally cylindrical shape collapses to a great extent to rush down along the internal wall of the tub thereby to crush the workpieces against the internal tub wall. Thus such a crusher relies upon the utilization of the centrifugal force exerted on the outermost portion of the mass sliding down along the internal wall of the rotating and revolving tub. This is distinctively different from the surface finishing method to which British Specification 1,047,703 and the present Specification relate, in which the centrifugal force is exerted only on a free

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surface layer of a mass which layer has successively different mass portions brought into and removed from it.

The invention provides a surface finishing method comprising loading a mixture of workpieces and abrasives into at least one barrel having an internal cross-section in the shape of an equilateral polygon having from five to eight sides in such a manner that a substantial free space is left in the barrel, causing the barrel to rotate in one direction about its own axis at a rate of n rotations per unit time, and at the same time causing the barrel to gyrate in the opposite direction about a fixed axis parallel to and located at a distance R from the axis of the barrel at a rate of N revolutions per unit time where R is greater than the radius r of the circumcircle of the equilateral polygon, the method being characterized in that, referring to a Cartesian orthogonal coordinate system (R/r, n/N), the method is carried out at an operating point [(r, N)] whose coordinates $\left(\frac{R}{r}, \frac{n}{N}\right)$ satisfy the relations

$$-1 > \frac{n}{N} \geq \left(-0.3\frac{R}{r} - 1\right)$$

and $1.5 \leq \frac{R}{r} \leq 8$.

The barrel may gyrate at a speed of $80/\sqrt{2R}$ r.p.m. or more in accordance with the specific gravity and fluidity of the mixture therein, where R is expressed in metres.

The invention is based upon the discovery that, upon surface finishing workpieces within a gyrating barrel with abrasives in such a manner that the polishing action is accomplished only on a free surface layer of a mixture of workpieces and abrasives in the barrel and that successive portions of the mixture are brought into and removed from the surface layer by the gyration of the barrel, a safe, efficient finishing operation can be performed by properly selecting the radii of revolution and rotation of the barrel, and the rates n and N of rotation and revolution of the barrel, for a negative value of n/N the absolute value of which is greater than unity.

Also it has been found that the barrel should have an internal cross-section in the shape of an equilateral polygon having from five to eight sides. If the barrel is in the shape of an equilateral triangle or square its side or diagonal is excessively greater than the minimum length of a straight line bisecting its cross-sectonal area. With a gyrating barrel of such a shape loaded to about 50% by volume, the centrifugal force due to the gyration of the barrel causes the surface layer of the mass in the barrel positioned on a surface passing through a diagonal to be transferred on the succeeding surface passing through the next one of the said straight area-bisecting lines in such a manner that the central portion of the surface layer is raised in the shape resembling a curling wave which, in turn, strikes against the opposite side of the barrel with the result that satisfactory surface finishing is not performed.

Wth a barrel having an internal cross-section in the shape of an equilateral polygon having from five to eight sides, the surface mass layer is smoothly transferred from one surface to the next without any curling wave occurring. On the other hand, a barrel having an internal cross-section in the shape of an equilateral polygon having nine or more sides resembles a barrel of circular cross-section in operation. A mass in such a barrel slides along the internal wall thereof resulting in uneven finishing.

It has further been found that the barrel should, as a rule, gyrate at a minimum speed corresponding to $80/\sqrt{2R}$ r.p.m. where R is the radius of revolution of the barrel in metres. It will be understood that the higher the speed the higher the polishing efficiency will be. However, in view of the standpoint of the mechanical strength of presently available materials for the apparatus, the maximum speed of gyration will generally be $350/\sqrt{2R}$ r.p.m.

The proportion of workpieces to abrasives is preferably not less than 1:10 by volume. A mixture of workpieces and abrasives having the proportions just specified is loaded in a barrel such as above described in an amount equal to from 40 to 70% and preferably to from 50 to 60% on the basis of the internal volume of the barrel.

Abrasives used with the invention may be organic, inorganic or metallic materials

e.g. in the form of a slurry, or solid e.g. a powder or a spherical solid or mixtures thereof.

The invention is equally applicable to wet or dry finishing processes.

The invention will be further described in conjunction with the accompanying drawings in which:—

Figure 1 is a front elevational view of an apparatus operable in accordance with the invention;

Figure 2 is a side elevational view of the apparatus as viewed on the right-hand side of Figure 1;

Figure 3 is a fragmental side elevational view, partly in section, of a drive for rotating and revolving a barrel in opposite directions;

Figure 4 is a sectional view of barrels of different radial dimensions capable of being selectively mounted in a barrel housing shown in Figures 1 and 2 with the distance R between the axes of revolution and rotation of the barrel remaining unchanged, the section being taken along the line IV—IV of Figure 2;

Figure 5 is a view similar to Figure 4 but illustrating barrels of the same radial dimension disposed at different distances from the axis of revolution thereof;

Figure 6 is a view similar to Figure 4 but illustrating the case in which $\frac{R}{r}$ has different values while $R+r$ remains unchanged;

Figure 7 is a diagram useful in calculating the speed of an arbitrary point on a barrel;

Figure 8 is a diagram useful in obtaining an equation for a locus described by the point A shown in Figure 7;

Figure 9 is a graph plotting centrifugal force on each of three preselected portions of the barrel against the ratio of the rates n and N of rotation and revolution of the barrel;

Figure 10 is a graph illustrating the experimental relationship between the total amount of workpieces removed in polishing and the rate of revolution of the barrel with R, r constant and $n/N=-1$;

Figure 11 is a graph illustrating the relationship between polishing efficiency and n/N with R and r constant;

Figure 12 is a graph plotting the centrifugal force and the polishing efficiency against R for $n/N=-1$;

Figure 13 is a graph plotting the polishing efficiency against n/N for different values of R/r;

Figure 14 is a graph illustrating the values of n/N with which the polishing efficiency is maximum for different values of R/r;

Figure 15 is a graph illustrating the dependence of the polishing efficiency upon both n/N and R/r with r and N remaining unchanged;

Figure 16 is a graph plotting the polishing efficiency against n/N for different values of R/r with $R+r$ remaining unchanged;

Figure 17 is a graph illustrating a curve for the maximum polishing efficiency and a curve for polishing efficiency with $n/N=-1$ against R/r, and

Figure 18 is a graph illustrating the efficient ranges of n/N and R/r taught by the invention.

The apparatus illustrated comprises a framework 10 of U-shaped cross-section, a main horizontal shaft 12 journalled at both ends in a pair of bearings 14, 14 disposed on the legs of the U, and a pair of spaced support discs 16, 16 secured adjacent to one end portion of the main shaft 12 and having sandwiched therebetween a plurality of sleeves 18 disposed at substantially equal angular intervals on the outer peripheral portion. A cylindrical housing 20 is carried in cantilever fashion by a barrel shaft 22 supported in each sleeve 18 and has mounted therein one of a plurality of barrels 24a, b and c of different radial dimensions (see Figure 4). While the barrel 24 is shown as having a hexagonal cross-section it is to be understood that its cross-section may be a regular pentagon, heptagon or octagon as previously pointed out.

Each barrel shaft 22 is provided at that end remote from the associated housing 20 with a sprocket wheel 26, each sprocket wheel being coupled through an endless chain 30 to a different one of a plurality of aligned sprocket wheels 28 mounted on the main shaft 12 for rotation relative to the latter, the wheels 28 being integral with each other.

An electric motor 32 is rigidly secured on the bottom portion of the framework 10 and has a pulley 34 secured on its output shaft (not shown). The pulley 34

is operatively coupled to another pulley 36 mounted on the main shaft 12 at one end through an endless belt 38. Another electric motor 40 suitably fixed on the framework 10 has a pulley 42 mounted on its shaft to be operatively coupled to a speed change gearing 44 through an endless belt 46 and an input pulley 48 to the gearing 44. The latter includes an output pulley 50 operatively coupled to a preselected one of the sprocket wheels 28 through an endless belt 52. With the arrangement illustrated the motor 32 is rotated in the direction of the solid arrow 54 (Figure 3) to drive the support discs 16 in the direction of the arrow 55 while the motor 40 may be rotated in the direction of the arrow 56 or arrow 57 to drive the sprocket wheels 28 and therefore the housings and barrels 20 and 24 in the direction of the arrow 58 or arrow 59 (see Figure 3).

From the foregoing it will be appreciated that when the discs 16 are rotated at a uniform speed in the direction of the arrow 55 about the axis of the main shaft 12 and simultaneously the barrels 24 are rotated about the axes of shafts 22 at a uniform speed in the direction of arrow 58 or 59 i.e. in the same direction as or the opposite direction to the direction of rotation of the supports, the motion of the support discs and barrels will resemble gyration of the barrels fixed to the discs.

As previously described the support discs 16 can be as a rule, revolved at a high speed equal to or greater than $80/\sqrt{2R}$ r.p.m. In these circumstances, a mass or a mixture of workpieces and abrasives in the gyrating barrel tends to be held against those portions of the internal wall of the barrel which are farthest from the axis of rotation of the discs; if the barrels are not driven, the ratio $n/N=0$. If the support discs 16 and barrels 24 are driven in the same direction as shown by arrows 55 and 58 in Figure 3, the ratio n/N may be considered to be positive while if they are driven in opposite directons as shown by the arrows 55 and 59 the ratio n/N will be negative. With the ratio n/N positive, the mass within the barrel will flow in the direction of the arrow 60 shown in Figure 3. On the other hand, a negative value of the ratio n/N will cause the mass to slide in the direction of the arrow 61 shown in Figure 3.

It will be readily understood that the larger the value of R the higher the centrifugal force and hence the polishing efficiency will be.

The motion of the support discs 16 and barrels 24 as above outlined will now be theoretically described in conjunction with Figure 7. In Figure 7, it is assumed that a support disc such as shown in Figures 1 and 2 is rotated about its centre of rotation represented by the origin O of a cartesian orthogonal coordinate system (x, y) while at the same time a barrel such as shown in Figures 1 and 2 is rotated about its centre of rotation O′ lying on a fixed circle whose centre is at the origin O. Since the barrel has an internal cross-section in the shape of an equilateral polygon it is represented in Figure 7 and the following Figures by the circumcircle (of radius r) of the polygon. It is further assumed that at any given time the centre O′ of the barrel assumes an angular position α with respect to the x axis and a preselected point A on the barrel circle has an angular position β with respect to the x axis.

Then the point A has a linear velocity V_1 due to revolution of the disc and a linear velocity V_2 due to rotation of the barrel expressed by the following equations

$$(1)\quad \begin{cases} V_1=2\pi RN \\ V_2=2\pi rn \end{cases}$$

where R is the radius of rotation of the disc, r the distance of the point A from the centre O′ of the barrel, and N and n are the rates of rotation of the disc and barrel. The two vectors V_1 and V_2 are vectorially added to provide the velocity of the point A, which is expressed by the equation

$$(2)\qquad V^2=(2\pi N)^2\left[(x^2+y^2)\left(1+\frac{n}{N}\right)+\frac{n}{N}r^2\left(1+\frac{n}{N}\right)-\frac{n}{N}R^2\right]$$

where x and y represent the coordinates of the point A.

Figure 8 which is similar to Figure 7 is useful in obtaining an equation for the locus of the point A during the movement as above described. When the radius vector OO′ has been rotated about the origin O through an angle ϵ and is located in its position OO″ the radius vector O′A is rotated through an angle $\beta+\epsilon$ with respect to

the x axis and further through angle $\epsilon\frac{n}{N}$ during rotation of vector OO′ through the angle ϵ until it reaches its position O″A′. Therefore the equation for the locus of the point A is expressed by the equations

$$(3)\quad \begin{aligned} x &= R\cos(\alpha+\epsilon)+r\cos[\beta+\epsilon(1+\frac{n}{N})] \\ y &= R\sin(\alpha+\epsilon)+r\sin[\beta+\epsilon(1+\frac{n}{N})] \end{aligned}$$

Since the radius of curvature ρ at any point on a curve $y=F(x)$ is defined by the equation

$$(4)\quad \rho=\frac{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{3/2}}{\frac{d^2y}{dx^2}}$$

the radius of curvature ρ at any point on the locus expressed by the equations (3) is given by the equation

$$(5)\quad \rho=\frac{\left[R^2+r^2(1+\frac{n}{N})^2+(1+\frac{n}{N})(x^2+y^2-R^2-r^2)\right]^{3/2}}{R^2+r^2(1+\frac{n}{N})^3+\frac{1}{2}(1+\frac{n}{N})(2+\frac{n}{N})(x^2+y^2-R^2-r^2)}$$

In terms of the acceleration g due to gravity the acceleration due to the centrifugal force on the point A can be expressed by $V^2/\rho g$. The equations (2) and (5) are substituted in $V^2/\rho g$ resulting in

$$(6)\quad \frac{V^2}{\rho g}=\frac{(2\pi N)^2}{g}\cdot\frac{R^2+r^2(1+\frac{n}{N})^3+\frac{1}{2}(1+\frac{n}{N})(2+\frac{n}{N})(x^2+y^2-R^2-r^2)}{\left\{R^2+r^2(1+\frac{n}{N})^2+(1+\frac{n}{N})(x^2+y^2-R^2-r^2)\right\}^{1/2}}$$

The above equation (6) can be used to calculate the centrifugal force exerted on any point on or in the circle O′.

In order to determine the limits of n/N and R/r for satisfactory surface finishing, it is necessary only to calculate the centrifugal forces on a few special points on the circle O′. To this end, the centrifugal forces were calculated for three points meeting the relationships.

$$x^2+y^2=(R\pm r)^2$$

and

$$x^2+y^2=R^2+r^2$$

Where $x^2+y^2=(R\pm r)^2$ the two points are farthest from and nearest to the origin O respectively and designated by the reference Roman numerals I and III in Figure 9, and where $x^2+y^2=R^2+r^2$ the point lies on each of the intersections of the circle O′ and a diameter perpendicular to the diameter passing through the points I and

III, the said point being designated by the reference Roman numeral II in Figure 9. The centrifugal forces on the points I, II and III are expressed respectively by the equations

$$\frac{V^2}{\rho g}(\mathrm{I}) = \frac{(2\pi N)^2}{g}\left[R + r\left(1+\frac{n}{N}\right)^2\right]$$

$$\frac{V^2}{\rho g}(\mathrm{II}) = \frac{(2\pi N)^2}{g}\;\frac{R^2 + r^2\left(1+\frac{n}{N}\right)^3}{\left[R^2 + r^2\left(1+\frac{n}{N}\right)^2\right]^{1/2}}$$

$$\frac{V^2}{\rho g}(\mathrm{III}) = \frac{(2\pi N)^2}{g}\left[R - r\left(1+\frac{n}{N}\right)^2\right]$$

The centrifugal force on the point II is nearly equal to that on the centre O′ of the barrel.

Assuming that N=180 r.p.m., R=30 cm and r=10 cm, the values of the centrifugal forces on the points I, II and III are illustrated in Figure 9 wherein the abscissa represents n/N and the ordinate represents $V^2/\rho g$. Curves I, II and III are plotted for the points I, II and III respectively. The useful range of n/N can be determined from curves I, II and III as will be subsequently described.

For a centrifugal force whose value is negative at the innermost point III, a mass in the barrel begins to stick against the entire internal wall of the barrels. Therefore the centrifugal force at that point must be positive.

In other words, the value of n/N should hold the following relationship

$$(7)\qquad \sqrt{\frac{R}{r}} - 1 > \frac{n}{N} > -\left(\sqrt{\frac{R}{r}} + 1\right)$$

for example, for R/r=3, n/N must meet the following inequality

$$0.732 > \frac{n}{N} > -2.732$$

This shows that the useful range of n/N is extremely narrow.

To calculate polishing efficiency, experiments were conducted with only N variable under the following conditions:

Machine used: High speed gyration barrel finishing machine sold by the applicant.

Barrel type: Hexagonal shape horizontally disposed.

Barrel size: 164 mm inside minimum dimension and 275 mm length.

Radius of revolution R: 268 mm.

Abrasives: Standard chips sold by the applicants and consisting essentially of 68% of alumina and 32% of a bonding material or silica by weight, formed in spheres whose diameter is of 6±0.5 mm.

Charge: 50% of internal volume of barrel.

Water: 1 litre.

Compound: 10 g of CO-200 (Trade Mark) including 70% $Na_4P_2O_7$—30% $NaNO_2$.

Time: One hour.

The results of experiments are illustrated in Figure 10 wherein the abscissa represents the polishing efficiency i.e. the amount Q of metal removed in grams in polishing and

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the ordinate represents the number N of revolutions per minute, n being equal to N. The curve illustrated in Figure 10 can be expressed by the equation

$$Q=K''N^{2.48} \tag{8}$$

where K'' is a constant.

Assuming that the amount of metal removed in polishing is proportional to the number n/N of sliding movements of the mass per complete rotation of the disc, the rate of rotation N of the latter and the Sth power F^s of the value of the centrifugal force F exerted on the central portion of the mass, the relationship between the centrifugal force and the amount Q removed from the workpieces is expressed by the equation

$$Q=K_1N\frac{n}{N}F^s;\quad \text{if } n=N:$$

$$Q=K_1NF^s \tag{9}$$

Comparing equation (8) with equation (9) and considering that F is proportional to N^2, s is determined to be equal to 1.24.

F is expressed by

$$F=\frac{(2\pi N)^2}{g}\,\frac{R^2+r^2(1+\frac{n}{N})^3}{\left[R^2+r^2(1+\frac{n}{N})^2\right]^{1/2}}$$

Therefore the polishing efficiency is expressed by the equation

$$Q=K'N^{2s}\,|n|\left\{\frac{R^2+r^2(1+\frac{n}{N})^3}{\left[R^2+r^2(1+\frac{n}{N})^2\right]^{1/2}}\right\}^s \tag{10}$$

where s has a value of 1.24. In Figure 11 wherein the abscissa represents n/N and the ordinate represents the polishing efficiency, the upper curve labelled "160 rpm" was plotted for N=160 rpm and the lower curve labelled "120 rpm" was plotted for N=120 rpm calculated from equation (10), plotted on a scale selected so that the polishing efficiency equals unity when n/N=−1 and N=160 rpm. The dotted circles and open circles designate the measured values of the polishing efficiency. For the upper curve illustrated in Figure 11, the relationship between n/N and the measured amount removed from the workpieces in polishing is listed in the following Table I.

Table I

Relationship between n/N and measured amount removed with N=160 rpm

Amount removed	n/N
390 mg	0.5
800 mg	−0.5
1,620 mg	−1.0
2,320 mg	−1.5
2,611 mg	−2.0

From Figure 11 it will be seen that the theoretical values of the polishing efficiency agree closely with the corresponding measured values within a range of n/N between 0 and −2. This means that equation (10) can be effectively used to

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calculate polishing efficiency of any gyration barrel finishing within the range of n/N just specified.

On the other hand, Figure 11 shows that for any positive value of n/N the theoretical values of the polishing efficiency are very different from the corresponding measured values thereof. For example, its measured value is a fraction of its corresponding theoretical value for $n/N=+0.5$. This shows that for $n/N=+0.5$ the centrifugal force on the point III as shown in Figure 9 is approaching zero value whereby a mass in a barrel has difficulty in effecting normal sliding motion and is in a floating state immediately before it sticks on the internal barrel wall.

As shown in Figure 11, any negative value of n/N having an absolute value exceeding 2 (two) causes the polishing efficiency to decrease but it greatly increases the centrifugal force on the point I as will be seen in Figure 9. For this reason, any negative value of n/N having an absolute value exceeding 2 is unsuitable for use in this case, that is, $R/r=3$.

Thus it has been found that the value of n/N should be negative rather than positive.

To determine the dependence of the polishing efficiency upon R/r experiments were conducted with an apparatus such as shown in Figures 1 and 2 wherein R is variable, $r=9.25$ cm, $N=240$ rpm and $n/N=-1$. Their results are illustrated in Figure 12 wherein the axis of abscissae represents R in cm while the righthand axis of ordinates represents the polishing efficiency Q relative to that at $R/r=3$ and $N=160$ rpm and the lefthand axis of ordinates represents the ratio of acceleration α of the point II (see Figure 9) to the acceleration g due to the gravitation. The solid curve shows the efficiency and the dotted curve shows the acceleration. As previously described, the larger R is, the higher the polishing efficiency will be. The data in Figure 12 clearly shows this. If delicate and/or brittle workpieces are subjected to an excessively high centrifugal force, then they are apt to be deformed and/or damaged. Therefore, the present invention is beneficial in that upon surface finishing delicate and/or brittle workpieces, a value of the centrifugal force suitable for them can be preliminarily determined.

The polishing efficiency will now be discussed with respect to the case where R/r is variable while R remains unchanged and the case where both n/N and R/r are variable in order to select the values of R and r. The change in polishing efficiency with R/r can be calculated from the equation (9) and is illustrated in Figure 13 wherein the abscissa represents n/N and the ordinate represents the polishing efficiency Q relative to that at $n/N=-1$ and $R/r=3$ and with a parameter being R/r, R being constant. Figure 13 corresponds to Figure 4 wherein a plurality of barrels such as hexagonal barrels 24a, b and c having different radial dimensions r_1, r_2 and r_3 are selectively mounted in coaxial relationship in the housing 20. Figure 13 shows that the larger is R/r, the higher is the polishing efficiency. This is because the workpieces contained in one barrel are relatively low in number.

As shown in Figure 5, a barrel 24 may be rotatably mounted on the support discs 16 at different distances R_1, R_2 and R_3 from the centre of rotation 0 of the disc, to vary R/r. The relative polishing efficiency of such an arrangement is calculated from equation (10) by varying R and n while r and N remain unchanged, and is illustrated in Figure 15 wherein the abscissae and ordinates have the same meaning, as in Figure 13. From Figure 13 it will be seen that the maximum value of the polishing efficiency and the range within which polishing can be satisfactorily accomplished depends upon R/r.

Figure 14 shows a curve for the maximum polishing efficiency referred to a Cartesian orthogonal coordinate system (R/r, n/N). The curve shown in Figure 14 can be expressed by the equation.

$$\frac{n}{N}=-0.3\frac{R}{r}-1 \qquad (11)$$

Since the range of n/N within which the polishing efficiency decreases with an increase in absolute value of n/N will increase the centrifugal force on the outermost point on the associated barrel as will be understood from the description for Figure 11, the invention contemplates to use value of n/N above the straight line shown in Figure 14. In other words, the equation (11) gives one limit of n/N.

Further R/r may be changed while R+r remains unchanged. For example, as shown in Figure 6, a plurality of barrels such as hexagonal barrels 24, 24′ and 24″

having different radial dimensions r_1, r_2 and r_3 may be selectively disposed at different distances R_1, R_2 and R_3 such that R_1+r_1, R_2+r_2 and R_3+r_3 are equal to each other. In this case the polishing efficiency is given by the equation

$$(12)\quad Q=K'r^{2+s}\,\frac{n}{N}\,N^{1+2s}\left[\frac{\left(\frac{R}{r}\right)^2+\left(1+\frac{n}{N}\right)^3}{\left\{\left(\frac{R}{r}\right)^2+\left(1+\frac{n}{N}\right)^2\right\}^{1/2}}\right]^s$$

wherein K' is a constant and s has been previously defined. Figure 16 wherein the abscissa and ordinate have the same meaning as in Figure 13 illustrates curves for equation (12) for various values of R/r. The negative numbers having a leading lines from adjacent to the maximum point on each curve are the particular values of n/N providing the corresponding maximum values of the polishing efficiency. From Figure 16 it will be seen that the smaller is R/r, the higher is the polishing efficiency. However it has been found that the polishing efficiency increase to a certain limit as R/r decreases and that it has a maximum value adjacent to $r/(R+r)=0.6$ or $R/r=2/3$, after which the polishing efficiency decreases. The data in Figure 17 show this. In Figure 17 the abscissae represent r/c, r/R and R/c where $c=R+r$ and the ordinates represent the relative polishing efficiency Q. Also there is shown a curve for the relative polishing efficiency at $n/N=-1$ or of the above cited British Patent No. 1,047,703.

Thus the ratio R/r can now be selected from a domain defined by the upper and lower curve portions shown in Figure 17.

From the foregoing it has been concluded that any negative value of n/N in excess of that providing a maximum value of the polishing efficiency as above described has no beneficial effect on the polishing process but merely increases the centrifugal force on the outermost position I of the barrel and accordingly increases the risk of damage to the workpieces. Also, as seen in Figure 11, any value of n/N between minus unity and zero decreases the distance through which a mass can slide down in the associated barrel. This is disadvantageous in that the polishing efficiency decreases and nevertheless the centrifugal force at the outermost portion of the barrel increases. Further any positive value of n/N is not at all advantageous as shown in Figure 11.

More specifically, if the absolute value of minus n/N increases beyond unity for any given value of R/r, then in the distance of sliding movement of a mass in a barrel increases and thereby the polishing efficiency increases. The above-mentioned maximum value of the polishing efficiency monotonically increases until the ratio n/N reaches a certain value (see Figure 11). However the centrifugal force on the surface layer of the mass in the barrel decreases as shown at curve II in Figure 9. This means that a large negative value of n/N makes it possible to surface finish workpieces into relative flat surfaces and is especially suitable for precise or glossy polishing.

Also it will be understood that the more the value of n/N approximates minus unity, the shorter the distance through which a mass slides in the associated barrel will be and therefore the higher the centrifugal force on the sliding mass will be. Therefore it is apparent that any negative value of n/N greater than and approximating minus unity is suitable for heavy grinding.

From the foregoing it has finally been concluded that surface finishing should be performed at an operating point positioned in a hatched domain shown in Figure 18. Referring to a Cartesian orthogonal coordinate system $(R/r, n/N)$, the hatched domain is defined by a straight line expressed by $\frac{n}{N}=-0.3\frac{R}{r}-1$ and a straight line expressed by $\frac{n}{N}=-1$, but excludes the latter line, and by a pair of straight lines expressed by $R/r=1.5$ and $R/r=8$ respectively. The equation $\frac{n}{N}=-0.3\frac{R}{r}-1$ represents the maximum values of the polishing efficiency.

Also in Figure 17, the hatched portion between the two curve portions designates an operating domain and its preferred domain for R/r and n/N with R+r remaining unchanged. Similarly the hatched portion defined by R/r=1.5 and R/r=8 and the preferred portion is defined by R/r=2 and R/r=5.

In order to change R/r, the arrangement shown in any of Figures 4, 5 and 6 may be used. The speed change gearing 44 is used to change n/N. Alternatively the motor 32 may be a variable speed motor. If desired, the main shaft 12 may change in speed of rotation to change n/N.

The results of tests indicated that the present method had a polishing efficiency equal to from 60 to 1000 times that of conventional rotating barrel finishing methods and to from 15 to 300 times that of conventional vibrating barrel finishing methods.

It is to be noted that when selecting the values of n/N and R/r, the material, shape and dimension of workpieces, the type of abrasives, etc. should be considered.

WHAT WE CLAIM IS:—

1. A surface finishing method comprising loading a mixture of workpieces and abrasives into at least one barrel having an internal cross-section in the shape of an equilateral polygon having from five to eight sides and in such a manner that a substantial free space is left in the barrel, causing the barrel to rotate in one direction about its own axis at a rate of n rotations per unit time, and at the same time causing the barrel to gyrate in the opposite direction about a fixed axis parallel to and located at a distance R from the axis of the barrel at a rate of N revolutions per unit time, where R is greater than the radius r of the circumcircle of the equilateral polygon, the method being characterized in that, referring to a Cartesian orthogonal coordinate system (R/r, n/N), the method is carried out at an operating point whose co-ordinates satisfy the relations $-1 > \frac{n}{N} \geq -0.3\frac{R}{r} - 1$ and $1.5 \leq \frac{R}{r} \leq 8$.

2. A surface finishing method as claimed in Claim 1, characterized in that the abrasives are one selected from the group consisting of organic, inorganic and metallic material and mixtures thereof and are in the form of a slurry or solid.

3. A surface finishing method as claimed in Claim 1 or 2, characterized in that the mixture of workpieces and abrasives is loaded in the barrel in an amount equal to from 40 to 70% on the basis of the internal volume of the barrel.

4. A surface finishing method as claimed in Claim 1, 2 or 3, characterized in that the proportion of the workpieces to the abrasives is not less than 1:10 by volume.

5. A surface finishing method as claimed in Claim 1, 2, 3 or 4, characterized in that the barrel gyrates at a speed of at least $80/\sqrt{2R}$ revolutions per minute where R is the radius of revolution in metres of the barrel.

6. A surface finishing method, substantially as herein described and illustrated in the accompanying drawings.

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Agents for the Applicant(s).

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1211710 COMPLETE SPECIFICATION

5 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 1

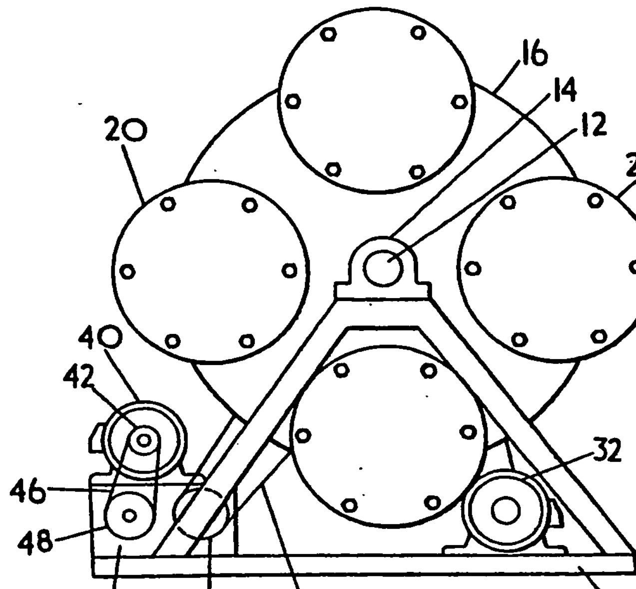

FIG.1.

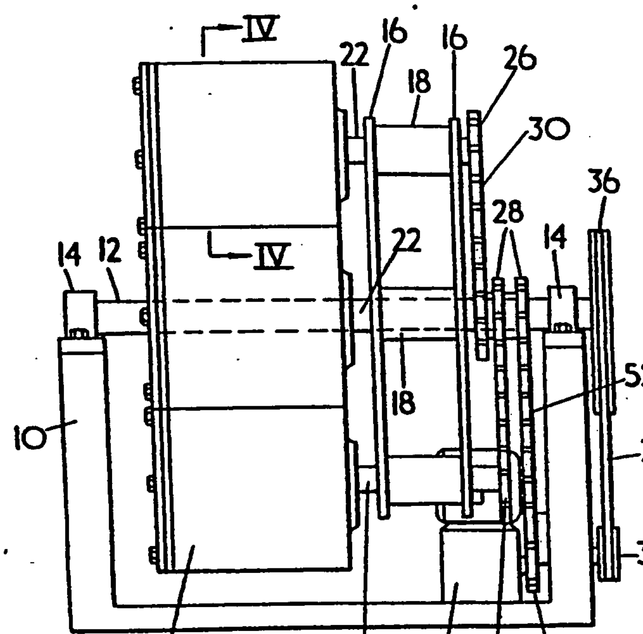

FIG.2.

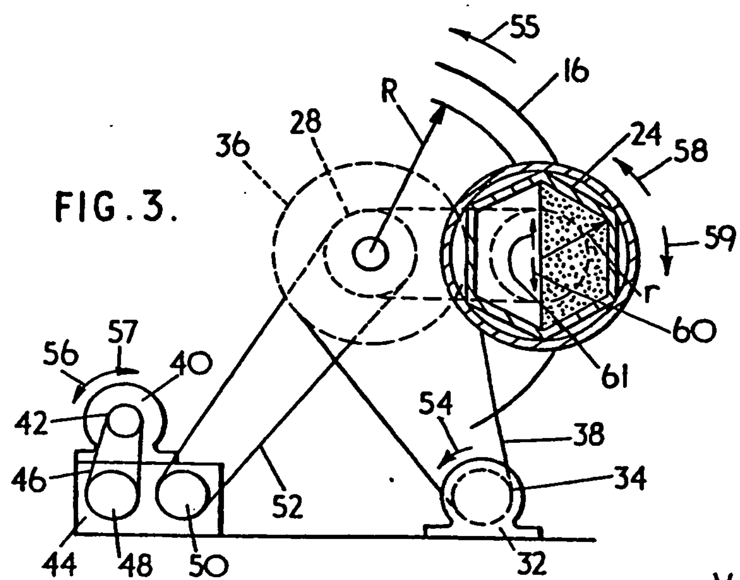

FIG. 3.

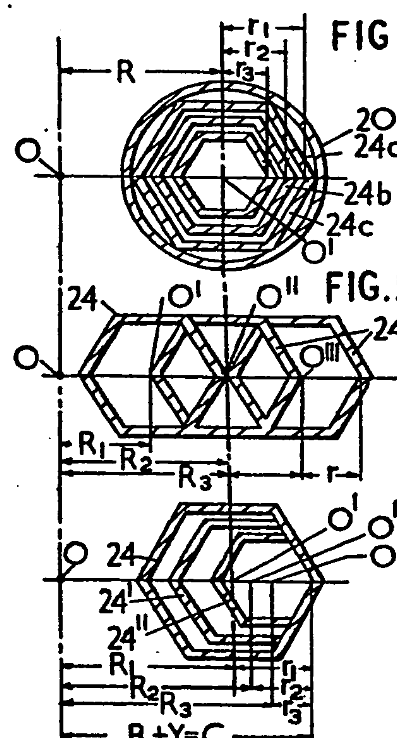

FIG. 4.

FIG. 5.

FIG. 6.

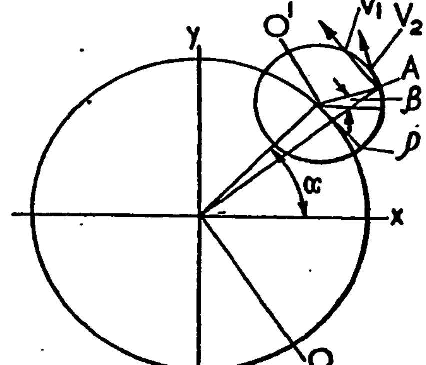

FIG. 7.

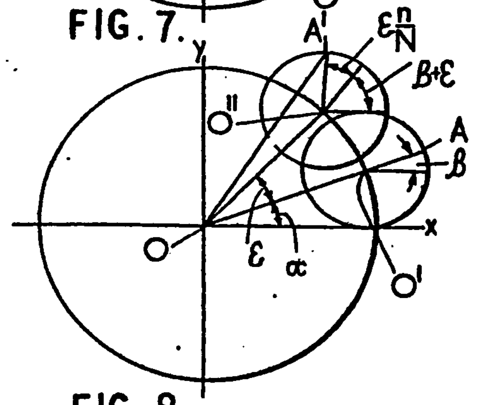

FIG. 8.

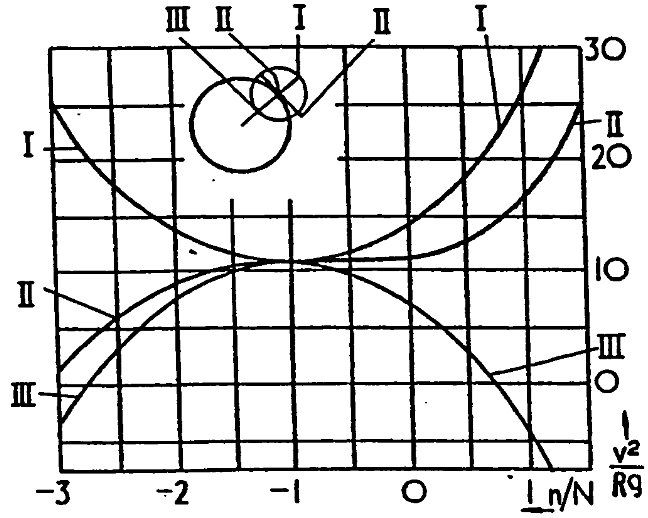

FIG.9.

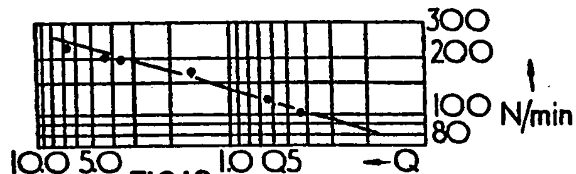

FIG.10.

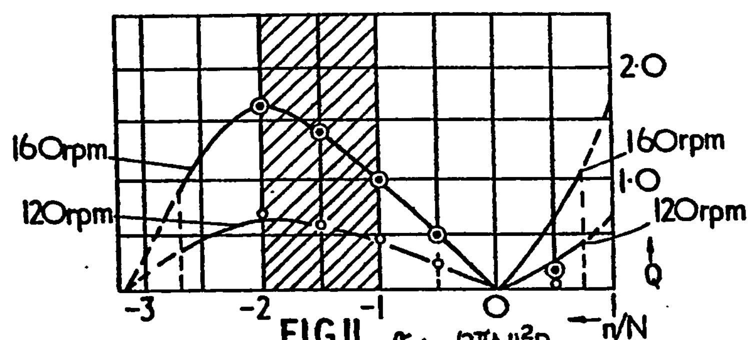

FIG.11.

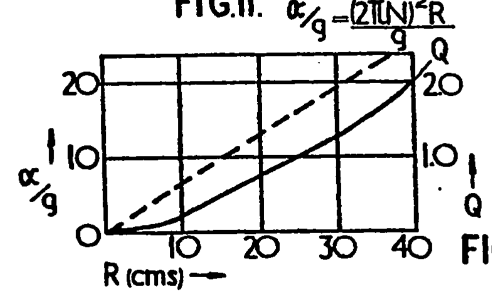

FIG.12.

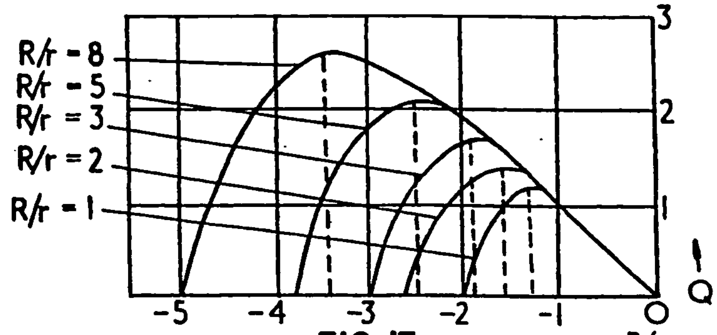

FIG.13.

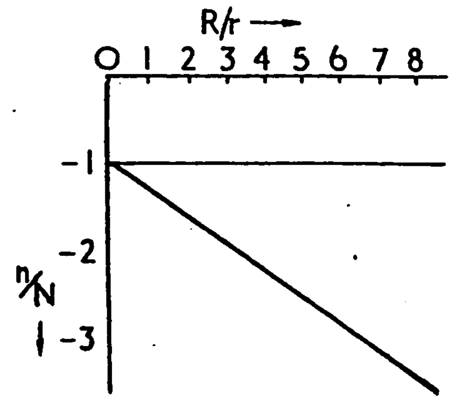

FIG.14.

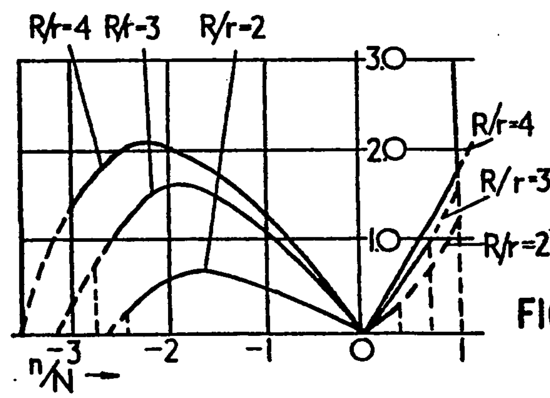

FIG.15.

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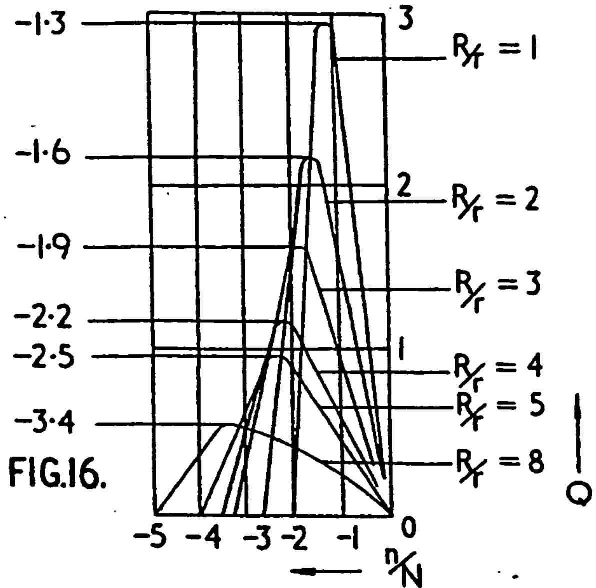

FIG.16.

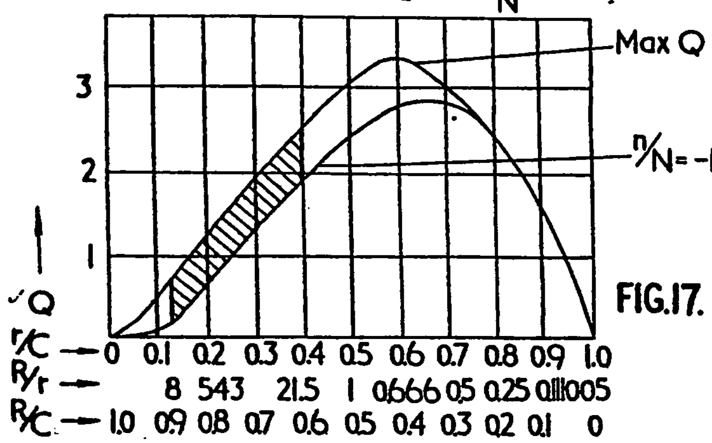

FIG.17.

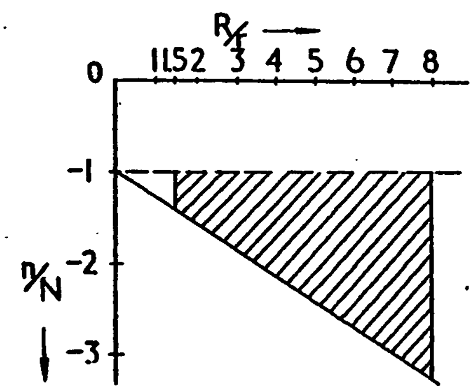

FIG.18.